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On the Neutrino Flares from the Direction of TXS 0506+056

Francis Halzen[1], Ali Kheirandish[1], Thomas Weisgarber[1], and Scott P. Wakely[2]
[1] Department of Physics & Wisconsin IceCube Particle Astrophysics Center, University of Wisconsin, Madison, WI 53706, USA
[2] Enrico Fermi Institute & Department of Physics, University of Chicago, Chicago, IL 60637, USA
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Abstract

A multimessenger campaign has associated a high-energy cosmic neutrino with a distant gamma-ray blazar, TXS 0506+056. IceCube archival data subsequently revealed that the high-energy neutrino flux from the direction of this source, integrated over the last 10 yr, is dominated by a single bright neutrino flare in 2014, leaving the multimessenger flare as a subluminous second flare. The extraordinary brightness of the blazar despite its distance suggests that it may belong to a special class of sources that produce cosmic rays. We show that the diffuse IceCube flux discovered in 2013 can be accommodated by a subclass of blazars, on the order of 5%, that episodically produce neutrinos with the luminosity of the 2014 neutrino flare. Matching the cosmic-ray flux required to produce the neutrinos to the one observed implies highly efficient neutrino sources with large target photon densities that are not transparent to high-energy gamma-rays. The opacity of the source modifies the straightforward multimessenger connection in a way that is consistent with the gamma-ray observations coincident with the 2014 neutrino flare.

Key words: astroparticle physics – BL Lacertae objects: general – BL Lacertae objects: individual (TXS 0506 +056) – galaxies: active – neutrinos

1. Introduction

The rationale for multimessenger astronomy is to search for the sources of cosmic rays by observing high-energy neutrinos and gamma-rays that originate in environments where protons are accelerated to produce pions and other particles that subsequently decay into neutrinos. Since 2013, IceCube has observed a diffuse flux of extragalactic neutrinos above 100 TeV with a power-law spectrum with spectral index $\gamma \sim -2.15$ to -2.2 (Aartsen et al. 2013, 2014, 2015, 2016; Kopper et al. 2015; Kopper & IceCube Collaboration 2017). In a multimessenger context, it has been recognized that the cosmic neutrino flux is surprisingly large, implying roughly equal energy densities in neutrinos and photons in the nonthermal universe (Ahlers & Halzen 2018). The matching energy densities of the extragalactic gamma-ray flux detected by the *Fermi* Large Area Telescope (*Fermi*-LAT) and the high-energy neutrino flux measured by IceCube may also suggest a common origin, possibly from blazars that dominate the *Fermi* source catalogs. Additionally, the even higher intensity of the neutrino flux below 100 TeV in comparison to the *Fermi* data might indicate that these sources are even more efficient neutrino than gamma-ray sources (Murase et al. 2016; Bechtol et al. 2017). Interestingly, the common energy density of photons and neutrinos is also comparable to that of the ultra-high-energy extragalactic cosmic rays (above 10^9 GeV). Unless accidental, this indicates a common origin and illustrates the potential of multimessenger studies.

However, until recently, the accumulating IceCube neutrinos had not revealed their origin (Aartsen et al. 2017; Reimann & IceCube Collaboration 2017). With the advantage of temporal coincidence, a flaring gamma-ray blazar, TXS 0506+056, was identified in follow-up observations as the source of a high-energy neutrino detected on 2017 September 22 (Aartsen et al. 2018a). Knowing where to look, the IceCube Collaboration scrutinized the archival data obtained from over a decade of detector operation, finding a large excess of neutrinos in a flare that lasted ∼110 days in 2014. This single flare dominates the flux of the neutrinos from the direction of TXS 0506+056 over the 10-year period of observations (Aartsen et al. 2018b).

In this paper, we focus on the 2014 neutrino burst identified in the archival data and investigate its relation to the diffuse neutrino flux observed by IceCube. Guided by the very large flux and luminosity produced by TXS 0506+056 in the 2014 flare, we study whether a subclass of blazars can explain the diffuse neutrino flux observed by IceCube. Subsequently, given the similar energy in cosmic rays and neutrinos, we use the energy content of the very high-energy cosmic rays to understand the workings of this subclass of sources.

We will show that a subset of about 5% of all blazars, bursting once in 10 yr at the level of TXS 0506+056 in 2014, can accommodate the diffuse cosmic neutrino flux observed by IceCube. Identification of the energy of the cosmic-ray flux necessary to accommodate the neutrinos with the one observed requires that the sources have a high efficiency for producing neutrinos and, as a consequence, are opaque to the accompanying high-energy gamma-rays. The large target photon densities required to accommodate the more than a dozen neutrinos produced in less than 3 months renders the source opaque to high-energy gamma-rays, and this provides the answer to a key question about the 2014 neutrino burst: where are the pionic high-energy gamma-rays that should accompany the high-energy neutrinos? Using the gamma-ray flux measurement from the *Fermi*-LAT satellite during the 2014 neutrino flare (Garrappa et al. 2019), we show that a consistent picture emerges when the source opacity creates a gamma-ray cascade at the source, followed by cascading to lower energies on the extragalactic background light (EBL) as the gamma-rays propagate out of the source to Earth.

While not proven, we show that a subclass of blazars with the emission characteristics of TXS 0506+056 can accommodate the observations of the highest energy cosmic rays and neutrinos. Our arguments are based on energy considerations and do not depend on the detailed blueprint of the accelerator.

However, the picture suggests that emission is dominated by extreme events where enhanced accretion onto the black hole results in acceleration of protons in radiation fields that are opaque to the high-energy photons routinely observed from blazars.

2. Time-dependent Neutrino Emission from TXS 0506+056

In a multimessenger campaign, TXS 0506+056 was identified as a likely source of a 290 TeV neutrino observed by IceCube in 2017 September (Aartsen et al. 2018a). The identification of the source led to an archival study of the time-dependent and time-integrated neutrino emission from the data collected in 9.5 yr of IceCube operation (Aartsen et al. 2018b). The time-dependent analysis revealed in 2014 a large burst of 13 ± 5 neutrinos over a period of 110 days. This observation yields a significance of 3.5σ, rejecting a background explanation for the events, and dominates the observed flux from the source over 10 yr of observation. During the flaring period, the measured spectral index is consistent with the one observed for the diffuse neutrino flux.

TXS 0506+056 is an intermediate synchrotron-peaked BL Lac object at a redshift of 0.34 (Paiano et al. 2018). During the 2014 burst, the neutrino flux was $1.6 \times 10^{-15}\,\mathrm{TeV^{-1}\,cm^{-2}\,s^{-1}}$ at 100 TeV (Aartsen et al. 2018b). The time-averaged flux of neutrinos from the source over 9.5 yr of IceCube observations was $0.8 \times 10^{-16}\,\mathrm{TeV^{-1}\,cm^{-2}\,s^{-1}}$ (Aartsen et al. 2018b).

The distance to TXS 0506+056 is more than 10 times greater than the distance to the nearest known blazar. Despite its distance, the source outshines other, nearer blazars in neutrinos, suggesting a special class of sources that accelerate protons and produce very high-energy gamma-rays and neutrinos. The isotropic neutrino luminosity of TXS 0506+056 during the 2014 burst is $1.2 \times 10^{47}\,\mathrm{erg\,s^{-1}}$. In Section 3, we use this luminosity to set the scale for calculating the contribution of the subclass of sources to the total flux of neutrinos. It is worth mentioning that TXS 0506+056 had already been identified as a unique blazar in EGRET observations dominating the sky among sources that produced at least two photons with energies above 40 GeV (Dingus & Bertsch 2001). Despite its large redshift, it is one of the brightest sources in *Fermi* catalogs (Garrappa et al. 2019).

3. A Diffuse Cosmic Neutrino Flux from Flaring Blazars

The extraordinary detection of more than a dozen cosmic neutrinos in the 2014 flare, despite the 0.34 redshift of the source, suggests that TXS 0506+056 belongs to a special class of sources that produce cosmic rays. The single neutrino flare dominates the flux of the source over the 9.5 yr of archival IceCube data, leaving IC 170922A as a less luminous second flare in the sample.

In this section, we suggest answers to three major questions: what is special about this source, can a subclass of blazars with similar characteristics accommodate the diffuse flux observed by IceCube, and how do these sources contribute to the flux of the very high-energy cosmic rays?

In order to calculate the flux of high-energy neutrinos from a population of sources, we follow Halzen & Hooper (2002) and relate the diffuse neutrino flux to the injection rate of cosmic rays and their efficiency to produce neutrinos in the source. For a class of sources with density ρ and neutrino luminosity L_ν, the all-sky neutrino flux is

$$\sum_\alpha E_\nu^2 \frac{dN_\nu}{dE_\nu} = \frac{1}{4\pi}\frac{c}{H_0}\xi_z L_\nu \rho, \tag{1}$$

where ξ_z is a factor of order unity that parameterizes the integration over the redshift evolution of the sources. For episodic sources, the relation can be adapted to a fraction $\mathcal{F}$ of sources episodically emitting flares of duration Δt over a total observation time T:

$$\sum_\alpha E_\nu^2 \frac{dN_\nu}{dE_\nu} = \frac{1}{4\pi}\frac{c}{H_0}\xi_z L_\nu \rho \mathcal{F}\frac{\Delta t}{T}. \tag{2}$$

Applying this relation to the 2014 TXS 0506+056 neutrino flare for a density of BL Lac objects (Mertsch et al. 2017) of $1.5 \times 10^{-8}\,\mathrm{Mpc^{-3}}$ yields

$$\begin{aligned}\sum_\alpha E_\nu^2 \frac{dN_\nu}{dE_\nu} &\simeq 7.4 \times 10^{-9}\,\mathrm{TeV\,cm^{-2}\,s^{-1}\,sr^{-1}}\\ &\times \left(\frac{\mathcal{F}}{4\pi}\right)\left(\frac{c/H_0}{4.3\,\mathrm{Gpc}}\right)\left(\frac{\xi_z}{0.7}\right)\left(\frac{L_\nu}{1.2 \times 10^{47}\,\mathrm{erg\,s^{-1}}}\right)\\ &\times \left(\frac{\rho}{1.5 \times 10^{-8}\,\mathrm{Mpc^{-3}}}\right)\left(\frac{\Delta t}{110\,\mathrm{day}}\right)\left(\frac{10\,\mathrm{yr}}{T}\right).\end{aligned} \tag{3}$$

The flux on the left-hand side of Equation (3) is $\sim 3 \times 10^{-11}\,\mathrm{TeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$, and thus the equation is satisfied for $\mathcal{F}$ of the order $\simeq 0.05$. This means that a special class of blazars that undergo $\sim$110 day duration flares with the luminosity observed for TXS 0506+056 once every 10 yr accommodates the observed diffuse flux of high-energy cosmic neutrinos.

Next, we investigate the implication of the fact that the energy densities of the cosmic neutrinos and the very high-energy cosmic rays are similar for the efficiency of the sources to produce high-energy cosmic neutrinos. The diffuse high-energy cosmic neutrino flux is related to the energy flux of the cosmic rays by

$$\frac{1}{3}\sum_\alpha E_\nu^2 \frac{dN_\nu}{dE_\nu} \simeq \frac{c}{4\pi}\left(\frac{1}{2}(1 - e^{-\tau_{p\gamma}})\xi_z t_H \frac{dE}{dt}\right), \tag{4}$$

where $dE/dt \sim (1\text{–}2) \times 10^{44}\,\mathrm{erg\,Mpc^{-3}\,yr^{-1}}$ is the injection rate of cosmic rays above 10^{16} eV (Ahlers & Halzen 2012; Katz et al. 2013). From Equation (3) it follows that the energy densities match for an optical depth of the protons in the photon target of $\tau_{p\gamma} \gtrsim 0.4$. This high efficiency requirement is consistent with the premise that a special class of efficient sources with a high photon density is responsible for producing the high-energy cosmic neutrino flux seen by IceCube. The sources must contain a sufficient target density of photons, even possibly protons, to generate the large value of $\tau_{p\gamma}$. It is clear that the emission of flares producing the large number of cosmic neutrinos detected in the 2014 burst must correspond to major accretion events onto the black hole lasting a few months. The pionic photons will lose energy in the source and the neutrino emission is not accompanied by a flare as was the case for the 2017 event. The *Fermi* data are consistent with the scenario proposed; they reveal photons with energies of tens of GeV but no flaring activity.

We finally show that the gamma-ray spectra observed by *Fermi* over the period of the 2014 neutrino burst are consistent with this scenario. With the low statistics of the high-energy gamma-ray measurements, the energetics represents a more robust measure for evaluating the connection, especially because the source is opaque to high-energy gamma-rays, as indicated by the large value of its opacity $\tau_{p\gamma}$. With these values, the pionic gamma-rays will lose energy inside the source before cascading in the EBL. One can illustrate this point by using the connection between the $p\gamma$ and $\gamma\gamma$ opacities introduced in Murase et al. (2016):

$$\tau_{\gamma\gamma} \approx \frac{\eta_{\gamma\gamma}\sigma_{\gamma\gamma}}{\eta_{p\gamma}\hat{\sigma}_{p\gamma}}\tau_{p\gamma}, \tag{5}$$

where $\hat{\sigma}_{p\gamma} \sim 0.7 \times 10^{-28}\,\mathrm{cm}^2$ and $\sigma_{\gamma\gamma} \simeq 6.65 \times 10^{-25}\,\mathrm{cm}^2$. We assume $\eta_{\gamma\gamma} \sim 0.1$ and $\eta_{p\gamma} \simeq 1$. The large value of $\tau_{p\gamma} \gtrsim 0.4$ requires that $\tau_{\gamma\gamma} \simeq \mathcal{O}(100)$. For this very high opacity of the source, it is impossible for the very high-energy pionic gamma-rays, with energies similar to those of the neutrinos, to leave the source. No flare is expected; it is still interesting to investigate whether the observed gamma-ray flux, which includes several high-energy photons, is consistent with our previous conclusions.

4. The High-energy Gamma-Ray Emission Accompanying the 2014 Flare

Due to the high opacity of the source, the gamma-ray flux initiated by neutral pion decays associated with the neutrino burst is reprocessed to lower energies and will not be directly observable. In the following, we refer to the spectrum of these pionic gamma-rays as "internal" to the source, in contrast to the "intrinsic" spectrum emerging from the source into the intergalactic medium. The shape of the intrinsic spectrum will be determined by the particle interactions within the source and the energy at which the source becomes transparent to gamma-rays, which in turn depend on the target photon energies and bulk Lorentz factor of the source. In the absence of a detailed model of the accelerator, we investigate the consistency of the overall picture, adopting a phenomenological model of the high-energy gamma-rays emerging from the source. The spectrum, after internal reprocessing, is parameterized as

$$\frac{dN}{dE} = AE^{-2}e^{-E_L/E - E/E_H}, \tag{6}$$

where E_L and E_H are low- and high-energy cutoffs, and the normalization A is matched to the lower bound on the total power emitted in gamma-rays, between 30 TeV and 3 PeV, consistent with the IceCube neutrino observations. Thus, we assume that there are no internal losses during reprocessing and that total power in gamma-rays is conserved. We further make the approximation that this gamma-ray spectrum is constant over the 110 days of the neutrino burst.

The intrinsic spectrum given by Equation (6) subsequently suffers attenuation via pair production interactions with the EBL. In principle, the electron–positron pairs produced in these interactions can upscatter cosmic microwave background (CMB) photons into the high-energy regime, producing a cascaded component of the spectrum in addition to the attenuated, direct emission (Aharonian et al. 1994; Plaga 1995). However, this cascade will only be observable if the intergalactic magnetic field (IGMF) is sufficiently weak for the pairs not to be deflected before cooling on the CMB. We model the effects of the EBL and IGMF using a particle-tracking simulation similar to the one presented in Arlen et al. (2014) and used by Archambault et al. (2017). This simulation accounts for the full relativistic cross sections of the pair production and inverse Compton scattering processes and allows for arbitrary EBL and IGMF evolution with redshift. Our model for the IGMF assumes a coherence length of 1 Mpc and uses the methods presented in Giacalone & Jokipii (1999) to achieve a smoothly varying randomly oriented field with strength B_{IGMF}. We adopt the EBL model of Gilmore et al. (2012), and we further assume that interactions with the CMB are the dominant energy loss mechanism for the pairs, although this is under debate (see, e.g., Broderick et al. 2012; Sironi & Giannios 2014; Menzler & Schlickeiser 2015; Chang et al. 2016). In running the simulation to model the observed photon spectrum coincident with the neutrino burst, we remove any gamma-rays that arrive with time delays larger than 110 days.

We find that a relatively large value of the low-energy cutoff, $E_L \gtrsim 100$ GeV, is required to produce consistency with the *Fermi* observations during the 2014 neutrino outburst. Thus, in our model the spectrum of the source must be significantly narrower than is conventionally assumed for the gamma-ray spectra of blazars. This highlights the need for a different production mechanism to be at work during the neutrino burst. Figure 1 shows our results for two sets of assumptions. For the first, we assume $E_L = 100$ GeV, $E_H = 1$ TeV, and $B_{\mathrm{IGMF}} = 3 \times 10^{-19}$ G. The cascade emission reproduces the *Fermi* data well. However, an IGMF this weak is in tension with recent results from the *Fermi* collaboration (Ackermann et al. 2018) and may not be viable. In our second example, we fix the low-energy cutoff and assume $B_{\mathrm{IGMF}} = 10^{-16}$ G, compatible with the *Fermi* limits. This allows us to raise the high-energy cutoff to $E_H = 20$ TeV because the cascade is strongly suppressed at lower energies. As shown in Figure 1, in this case the combined cascade and direct emission can accommodate the apparent hardening of the *Fermi* spectrum (Padovani et al. 2018) due to its contribution in the energy range above ~10 GeV, although the *Fermi* emission at lower energies would have to be produced by some other process. Although we only show the result for $E_H = 20$ TeV in Figure 1, we find that for $B_{\mathrm{IGMF}} = 10^{-16}$ G the direct emission for any value of E_H between 500 GeV and 20 TeV produces an acceptable description of the *Fermi* data above ~10 GeV.

5. Discussion and Conclusion

The evidence for neutrino emission from TXS 0506+056 has set a tipping point in the search for the sources of high-energy cosmic neutrinos. Getting all the elements of this puzzle to fit together is not easy, but they suggest that the blazar may contain important clues on the origin of cosmic neutrinos and cosmic rays. This breakthrough is just the beginning and raises intriguing questions. Here we tried to address a few of these questions: What is special about this source? Can the subclass of blazars to which it belongs accommodate the diffuse flux observed by IceCube? Are these also the sources of all high-energy cosmic rays or only of some?

We explored the contribution of a subclass of blazars with characteristics similar to those of TXS 0506+056 during the 2014 burst and what that means for total flux measurements in

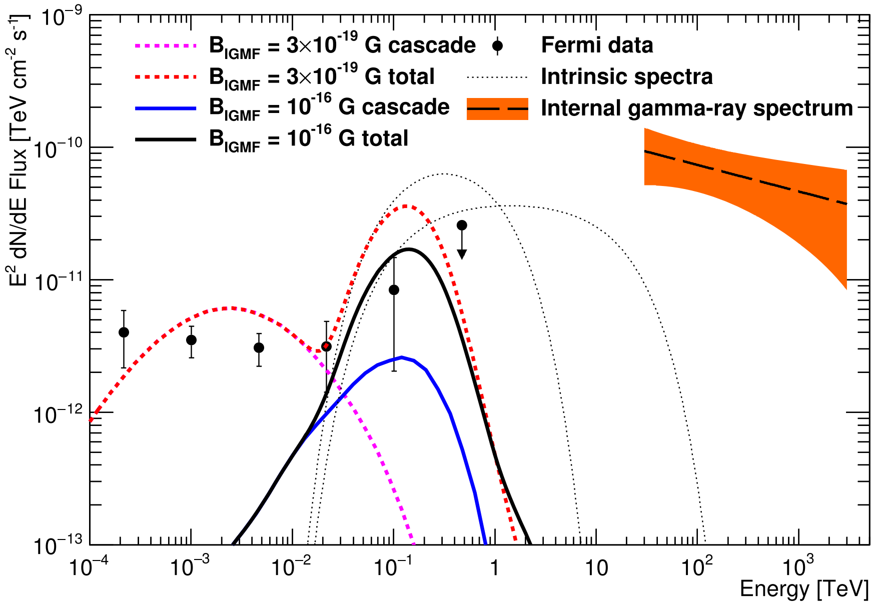

Figure 1. Observed cascade and total spectra for our model with $E_H = 20$ TeV and $B_{\mathrm{IGMF}} = 10^{-16}$ G (thick solid lines), and for $E_H = 1$ TeV and $B_{\mathrm{IGMF}} = 3 \times 10^{-19}$ G (thick dashed lines), along with the *Fermi* observations and internal pionic gamma-rays associated with the 2014 neutrino outburst. The low-energy cutoff is $E_L = 100$ GeV for both cases. The intrinsic spectra (thin dashed lines) for the two cutoff energies are given by Equation (6) and represent emission from the source after internal reprocessing but before attenuation on the EBL.

IceCube. The class of such neutrino-flaring sources represents 5% of the sources.

The high level of neutrino flux from TXS 0506+056 requires very efficient neutrino production at the source. We examined the efficiency by connecting the total neutrino flux to the energy content of the extragalactic cosmic rays, incorporating the common energy in high-energy cosmic neutrinos and the extragalactic cosmic rays. We find a high photohadronic efficiency that indicates high gamma-ray opacity of the sources. This means that the sources emit neutrinos more efficiently than they emit gamma-rays.

We further examined the gamma-ray emission during the dominant neutrino flare in 2014. Our results show that the absorption and interactions intrinsic to the source, followed by the interaction with the EBL, will result in a gamma-ray flux consistent with the *Fermi* observations. A gamma-ray flare is not expected when the source is a highly efficient neutrino emitter. We note that because we do not consider internal losses at the source, our estimated gamma-ray flux represents an upper limit on the expected gamma-ray emission accompanying the neutrinos in 2014.

Internal losses and cascades inside the source will produce a flux of photons at lower energies. The level of such flux can be used to constrain the opacity of the source and obtain a better understanding of particle acceleration and potential sites for the target radiation. Unfortunately, in the absence of real-time multiwavelength observations for the neutrino flare in 2014, a more detailed reconstruction of the accelerator is not possible. The study of the radio emission of TXS 0506+056 (Kun et al. 2019) suggests a small Lorentz factor that could indicate interactions happening close to the core of the AGN. Small Lorentz factors would support viable scenarios for jet power, avoiding unrealistic cosmic-ray luminosities. The case for a small Lorentz factor also follows arguments made in the context of a tentative observation of high-energy neutrinos by AMANDA in coincidence with a flare of 1ES 1959+560 in 2002 (Halzen & Hooper 2005).

The TXS 0506+056 neutrino emission over the last 10 yr is dominated by the single flare in 2014. If this is characteristic of the subclass of sources that it belongs to, identifying additional sources will be difficult unless more and larger neutrino telescopes yield more frequent and higher statistics neutrino alerts.

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ORCID iDs

Ali Kheirandish https://orcid.org/0000-0001-7074-0539

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